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Prediction of Pressure Characteristics in Settling Chamber of 0.6m Wind Tunnel for Supersonic Testing

SATYAJEET RATAN BHOI, G K SURYANARAYANA
National Trisonic Aerodynamic Facilities

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National Aerospace Laboratories
Bangalore 560 017, India

Prediction of Pressure Characteristics in Settling Chamber of 0.6m Wind Tunnel for supersonic testing

Satyajeet Ratan Bhoi ***G K Suryanarayana***

Abstract

It is proposed to augment the NAL 0.6m wind tunnel with a Variable Mach number Flexible Nozzle (VMFN) to enhance the testing capability from transonic to supersonic Mach numbers (up to 4.0). In order to avoid the start stop loads that are inherent in blow down wind tunnels, it is proposed to start the tunnel at a low Mach number (say 1.0) and then increasing the Mach number by reducing the nozzle throat (maximum Mach number = 4.0) by continuously flexing the nozzle walls; the reverse process is to be adopted while stopping. In such an operation, hvo important issues arise. Firstly, the settling chamber pressure should always be maintained above the minimum 'running'pressure at any supersonic Mach number to avoid flow breakdown in the test section. Secondly, in order to maintain the free-stream dynamic pressure constant during the useful runtime and within desirable limits during the transition from Mach 1.0 to 4.0 and vice versa. the Pressure Regulating Valve (PRV) must be operated in a closed - loop pressure control. In this report, the problem is formulated based on assumptions of quasi-steadv isentropic equations and a program is presented in C language to study the nature of variation of stagnation pressure in the settling chamberfor various trajectories of the opening of PRV and Mach number change. Good comparisons behveen the results predicted from the program and experimental data obtained at .subsonic Mach numbers in the existing 0.6m wind tunnel are shown. Predictions for VMFN operation show that the settling chamber pressure rapidly builds up towards the value of storage tank pressure, when the VMFN nozzle throat reduces from Mach 1.0 to Mach 4.0 condition. presumably due to constriction of the flow passage at the first throat. Likewise, the pressure rapidly falls when the VMFN reverses from Mach 4.0 to 1.0 condition. Bv suitably controlling the initial opening and the trajectory of opening and closing of the PRV. if is possible to ensure that the stagnation pressure in the settling chamber is always greater rhan the minimum (running) pressure that is necessary for stable flow in the test section. However. it is seen that during the transition from Mach 1.0 to 4.0 and vice versa. the free-srream dynamic pressure

overshoots to relatively high values, which has significance on model and balance design for aerodynamic force and moment measurements at supersonic Mach numbers in the 0.6m windtunnel.

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Symbols

a	speed of sound
A	area
m	mass flow
M	Mach number
n	expansion index
p	pressure
P	total pressure
r	pressure ratio
R	gas constant
t	time
T	temperature
u	velocity
V	volume
q	dynamic pressure
γ	ratio of specific heats
P	density

Subscripts

S	storage tank
SC	settling chamber
t	throat
v	valve
0	initial condition:
min	minimum
max	maximum

Supercript

*	sonic condition

1. Introduction

As a part of NTAF augmentation programme, it is proposed to augment the testing capability of the NAL 0.6m blowdown wind tunnel from transonic Mach nos to supersonic Mach nos up to 4.0. For this purpose, a Variable Mach number Flexible Nozzle (VMFN), driven by a single hydraulic jack is being developed. In blow-down wind tunnels, very high starting and stopping loads occur while testing at high supersonic Mach nos (Ref. I). In the 0.6m wind tunnel, it is proposed to start the VMFN at a low Mach no. (say. M = 1.0) and a low stagnation pressure and reach the test Mach no. (up to 4.0) to avoid starting loads. After completion of tests at the desired Mach no.. the VMFN would be brought back to Mach I.0 condition before shutting down the run, in order to avoid stopping loads. During the entire operation, the second throat would be kept fixed at a position corresponding to the starting condition at Mach 1.2 so that the normal shock during starting of the tunnel is anchored beyond the second throat at all supersonic Mach nos.

During the VMFN operation as described above, two important issues arise. Firstly, after the flow stabilizes at Mach 1.0 during start. it is essential to maintain a minimum stagnation pressure in the settling chamber using the Pressure Regulating Valve (PRV). to avoid supersonic flow breakdown in the test section. Secondly. since the storage tank pressure drops continuously as blowdown progresses; the PRV must be close-loop controlled to maintain constant dynamic pressure in the free-stream during the useful run. The available run time in the wind tunnel is governed by the mass flow rate, which in turn depends on the VMFN throat as well as opening area at the PRV, in addition to other parameters such as storage tank pressure, storage tank volume. losses at the PRV. etc. Thus, the problem of operation of VMFN involves the dynamics of Mach no. change and that of the PRV trajectory. besides the other fixed parameters related to the test facility. Further. in order to minimize the wastage of compressed air from the storage tank. it is required to reach the test Mach no. in the quickest possible time. after the flow is started at Mach I.0. However, during the entire blowdown, the dynamic pressure in the test section should not be undesirably high. since this affects the design of the model and the balance in supersonic Mach no. tests. It is therefore necessary to understand the stagnation pressure characteristics in the settling chamber, as a function of the VMFN throat (equivalent to Mach no.) as well as the PRV trajectory.

In this report, the problem is formulated based on quasi-steady isentropic equations to study the stagnation pressure characteristics in the settling chamber and the pressure drop in the storage tank for various opening and closing trajectories of the PRV when the Mach no. is varied from 1.0 to 4.0 and vice versa. A computer program in C language is presented to predict the settling chamber pressure characteristics. The program is validated with results from tests conducted in the 0.6m wind tunnel at few subsonic Mach nos. Predictions are made for the settling chamber pressure characteristics relevant to VMFN operation.

2. Project details

Title	: Prediction of Pressure Characteristics in Settling Chamber of 0.6m Wind Tunnel for supersonic testing
Project no.	: N-0-420
Sponsor	: NAL

3. Objectives and parameters of the problem

The desired output from the present exercise is to predict the following with respect to VMFN operation.

1. Effect of change of Mach no. (as well as the rate of change) from 1.0 to 4.0 on the settling chamber pressure for a fixed position of PRV (unregulated condition)
2. Effect of PRV trajectory on the settling chamber pressure and test section dynamic pressure as a function of Mach no..
3. Maximum available run-time at Mach 4.0 using various numbers of storage tanks (minimum volume of 25.000cft to maximum of 1.27.000cft)
4. To study whether an optimum trajectory for the PRV can be predicted. which ensures that

a) after the flow stabilizes at Mach 1.0 condition, the stagnation pressure is always higher than the minimum safe limit to avoid flow breakdown at any supersonic Mach no.,

b) wastage of compressed air is minimized by maximizing the useful run time in a run,

c) the dynamic pressure in the test section is not undesirably high during transition from M=1.0 to 4.0 and vice versa and is constant during the useful run time.

The parameters that decide the above issues are the volume of storage tanks (maximum 1,27.000 cft), the maximum initial storage tank pressure (163 psia), temperature (300K), volume of the settling chamber (up to VMFN throat for supersonic test conditions and up to second throat for subsonic and transonic test conditions), first throat area (at the VMFN), flow area and losses at the PRV.

4. Formulation of the problem

Figure 1 shows a schematic of the 0.6m wind tunnel. incorporating the VMFN. The governing equations for the mass flow rate through the PRV depend on whether the valve is choked or not, which in turn depends on the upstream and downstream conditions across the PRV and the opening area at the PRV. If the flow is choked. the mass flow is independent of pressure in the settling chamber and the variation of settling chamber pressure and the storage tank pressure are related through coupled linear equations. If the PRV is not choked. the entry mass flow depends on settling chamber pressure as well as the storage tank pressure, and the governing equations become coupled non-linear differential equations. These equations maybe solved using standard numerical methods.

4.1. Assumptions made

1. Polytropic expansion of air in the storage tank.
2. Stagnation temperature in the storage tank and the settling chamber are identical.

3. When the PRV is not choked, static pressure at the valve equals 0.96 times the settling chamber pressure.
4. When the VMFN throat is not choked, 5% loss of total pressure occurs at the throat.
5. Quasi-steady one-dimensional flow.
6. Isentropic flow equations are valid.

4.2. Mathematical formulation

Writing the continuity equation between storage tank and the valve (PRV),
rate of change of mass in storage tank = mass flow rate through the valve.

i.e.
$$-\frac{d\rho_s}{dt}V_s = \rho_v A_v u_v \tag{1}$$

For polytropic expansion with index n, and initial conditions P_{SO} and T_{SO}, the equation becomes.

$$-\frac{V_s}{n}\frac{P_{so}^{\frac{n-1}{n}}}{RT_{so}}P_s^{\frac{1-n}{n}}\frac{dP_s}{dt} = \rho_v A_v u_v \tag{2}$$

Writing the continuity equation between the valve and the test section.
mass flow rate through the valve = rate of mass buildup in settling chamber + mass flow rate through the throat.

i.e.
$$\rho_v A_v u_v = \frac{d\rho_{sc}}{dt}V_{sc} + \rho_t A_t u_t \tag{3}$$

Valve choked: The valve would be choked when' $\frac{p}{P_s} \le C$ where $C = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$

For this case.

$$\rho_v A_v u_v = \rho^* a A_v = C_1 \frac{P_s}{RT_{sc}}\sqrt{\gamma R T_{sc}}\, A_v \tag{4}$$

where $C_1 = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$

From (2) and (4), we have,

$$\frac{dP_s}{dt} = -\frac{nC_1}{V_S}\sqrt{\gamma RT_{S0}}\,\frac{1}{P_{so}^{\frac{n-1}{n}}}\,P_s^{\frac{2n-1}{n}}A_v \tag{5}$$

Valve unchoked The valve would be unchoked when $\frac{P}{P_s} > C$

For this case, we have,

$$\rho_v A_v u_v = \rho_v A_v \left(a_v M_v\right) \tag{6}$$

Now:

$$\rho_v = \frac{p_v}{RT_v}$$

Also. following the assumptions made in section 4.1, we have,

$$p_v = 0.96P_{sc} = P_s\left(1+\frac{\gamma-1}{2}M_v^2\right)^{-\frac{\gamma}{\gamma-1}}$$

$$T_v = T_{sc}\left(1+\frac{\gamma-1}{2}M_v^2\right)^{-1}$$

$$a_v = \sqrt{\gamma RT_v}$$

Substituting the above expressions in (6) and simplifying, we get

$$\rho_v A_v u_v = \sqrt{\frac{\gamma}{RT_{sc}}}A_v P_s f\left(r_v\right) \tag{7}$$

where $r_v = 0.96 P_{sc}/P_s$

and $$f(r) = \left[\frac{2}{\gamma - 1} r^{\frac{2}{\gamma}} \left(1 - r^{\frac{\gamma-1}{\gamma}}\right)\right]^{\frac{1}{2}} \tag{8}$$

Substituting (7) in (2), and simplifying we get,

$$\frac{dP_s}{dt} = -\frac{nf(r_v)}{V_S}\sqrt{\gamma R T_{S0}}\,\frac{1}{P_{s0}^{\frac{n-1}{n}}} P_s^{\frac{2n-1}{n}} A_v \tag{9}$$

Throat choked The throat would be choked when $\frac{p_{atm}}{P_{sc}} \leq C$

For this case,

$$\rho_t A_t u_t = \rho^* a^* A_t = C_1 \frac{P_{sc}}{RT_{sc}}\sqrt{\gamma R T_{sc}}\, A_t \tag{10}$$

Throat unchoked The throat would be unchoked when $\frac{p_{atm}}{P_{sc}} > C$

For this case, we have,

$$\rho_t A_t u_t = \rho_t A_t (a_t M_t) \tag{11}$$

Now,

$$\rho_t = \frac{p_t}{RT_t}$$

Also. following the assumptions made in section 4.1, we have,

$$p_t = 0.95 P_{sc}\left(1 + \frac{\gamma - 1}{2} M_t^2\right)^{-\frac{\gamma}{\gamma-1}}$$

$$T_t = T_{sc}\left(1 + \frac{\gamma - 1}{2} M_t^2\right)^{-1}$$

$$a_t = \sqrt{\gamma R T_t}$$

Substituting the above expressions in (11) and simplifying, we get.

$$\rho_t A_t u_t = \frac{0.95\, P_{sc}}{\sqrt{\gamma R T_{sc}}} A_t f(r_t) \tag{12}$$

where $r_t = p_{atm} / (0.95 P_{sc})$

(5) and (9) are the differential equations for the storage tank pressure variation for valve choked and unchoked cases respectively. These equations may be rewritten as a single equation as

$$\frac{dP_s}{dt} = -\frac{nF(r_v)}{V_S}\sqrt{\gamma R T_{S0}}\, \frac{1}{P_{so}^{\frac{n-1}{n}}} P_s^{\frac{2n-1}{n}} A_v \tag{13}$$

To obtain the settling chamber pressure equation, the expressions (10) and (12) are substituted in (3) for throat choked and unchoked cases respectively and simplified.

$$\frac{1}{\sqrt{\gamma R T_{so}}} \frac{dP_{sc}}{dt} + \frac{A_t}{V_{sc}} P_{sc} F(r_t) = \frac{P_s}{V_{sc}} A_v(t) F(r_v) \tag{14}$$

where

$F(r_v) = C_1$	if valve is choked
$= f(r_v)$	if valve is unchoked
$F(r_t) = C_1$	if throat is choked
$= f(r_t)$	if throat is unchoked

(13) and (14) constitute a pair of coupled non-linear differential equations for the variation of P_s and P_{sc} with time respectively.

The static pressure can be obtained from the relation

$$p = P_{sc}\left(1 + \frac{\gamma - 1}{2}M^2\right)^{-\frac{\gamma}{\gamma - 1}}$$

and the dynamic pressure by

$$q = \frac{\gamma}{2}pM^2$$

5. Method of solution

Fourth order Runge-Kutta numerical method is employed to solve the differential equations. Non dimensionalising P_s and P_{sc} with respect to the initial storage tank pressure, P_{so}, we get,

$$\overline{P}_s = \frac{P_s}{P_{so}} \quad \text{and} \quad \overline{P}_{sc} = \frac{P_{sc}}{P_{so}}$$

the initial conditions when t = 0 are.

$$\overline{P}_s = 1.0, \quad \overline{P}_{sc} = \frac{p_{atm}}{P_{so}} \tag{15}$$

From (13) and (14) we have

$$\frac{d\overline{P}_s}{dt} = F_1\left(t, \overline{P}_s\right)$$

$$\frac{L\overline{ip}\$<}{Lit} = F_2\left(t, \overline{P}_s, \overline{P}_{sc}\right)$$

where

$$F_1 = -\frac{n}{V_s}\sqrt{\gamma R T_{so}}\left(\overline{P}_s\right)^{\frac{2n-1}{n}} A_v(t) F(r_v)$$

$$F_2 = \frac{\sqrt{\gamma R T_{so}}}{V_{sc}}\left[\overline{P}_s A_v(t) F(r_v) - A_t k \overline{P}_{sc} F(r_t)\right]$$

where k = 1 for choked throat

= 0.95 for unchoked throat

With the initial conditions being defined by (15), the increments in $\overline{P}_s$ and $\overline{P}_{sc}$ at any time t, are given by,

$$\Delta\overline{P}_s = \frac{1}{6}\left(K_{11} + 2K_{12} + 2K_{13} + K_{14}\right)$$

$$\Delta\overline{P}_{sc} = \frac{1}{6}\left(K_{21} + 2K_{22} + 2K_{23} + K_{12}\right)$$

where,

$$K_{11} = F_1\left(t, \overline{P}_s\right)\Delta t$$

$$K_{21} = F_2\left(t, \overline{P}_s, \overline{P}_{sc}\right)\Delta t$$

$$K_{12} = F_1\left(t + \frac{1}{2}\Delta t, \overline{P}_s + \frac{1}{2}K_{11}\right)\Delta t$$

$$K_{22} = F_2\left(t + \frac{1}{2}\Delta t, \overline{P}_s + \frac{1}{2}K_{11}, \overline{P}_{sc} + \frac{1}{2}K_{21}\right)\Delta t$$

$$K_{13} = F_1\left(t + \frac{1}{2}\Delta t, \overline{P}_s + \frac{1}{2}K_{12}\right)\Delta t$$

$$K_{23} = F_2\left(t + \frac{1}{2}\Delta t, \overline{P}_s + \frac{1}{2}K_{12}, \overline{P}_{sc} + \frac{1}{2}K_{22}\right)\Delta t$$

$$K_{14} = F_1\left(t + \Delta t, \overline{P}_s + K_{13}\right)\Delta t$$

$$K_{24} = F_2\left(t + \Delta t, \overline{P}_s + K_{13}, \overline{P}_{sc} + K_{23}\right)\Delta t$$

6. Computer program

A computer program has been written using C language based on the method described above. The input data to the program are V_S, V_{SC}, A_t, dM/dt, dA_v/dt, n, γ, R, P_{atm}, P_{S0}, and P_{SC0}. The program evaluates the variation of P_S and P_{SC} and also computes the q. Appendix **A** includes listing of the program.

7. Results and discussions

7.1. Validation of the method

6089	0.2	30	81.72	90.000
6091	0.5	30	112.50	90.000
6092	0.6	30	106.00	90.000

The computer program was run for each of the above cases to obtain the P_{SC} and P_S characteristics. The measured valve-opening trajectory during the blowdown numbers 6089. 6091 and 6092 of 0.6m wind tunnel was used as input. The valve opening trajectories for the run numbers 6089, 6091 and 6092 are shown in Figures

2, 5 and 8 respectively. Figures 3, 6 and 9 show the comparison of the predicted P_{SC} characteristics with the test run data. It is seen that except for the initial build-up of P_{SC} for M=0.2, the predicted pressure agrees well with the experimental data. Figures 4, 7 and 10 show the predicted P_S drop with time compared with the test run data. Good comparison between the predicted and experimental results can be seen.

7.2. Minimum stagnation pressures in 0.6m wind tunnel at supersonic Mach nos

In order to achieve supersonic Mach nos in the test section, the second throat must be set to the 'starting' condition and the appropriate P_{SC} must be chosen to enable the normal shock at start to pass through the test section and locate itself in a stable position downstream of the second throat. After the flow starts, the second throat may be reduced to the 'running' condition, which enables supersonic operation at a lower P_{SC} and hence increases the run time. If P_{SC} falls below this minimum value P_{min}, the test section flow breaks down into a subsonic condition. resulting in large oscillatory loads, In case of VMFN, since the flow is started at M=1.0 with sufficiently wide second throat, P_{min} would be corresponding to the 'running' pressure. However, since P_{min} is not a priori known, starting pressure in the 1.2m wind tunnel is used as reference. Table 2 shows the values of P_{min} corresponding to some M chosen for the 0.6m tunnel. It is desirable to have the P_{SC} at least 5psi higher than the P_{min}, at any time during the blowdown.

Table 2

M	P_{min} (psia)
1	25
1.2	25
2	30
2.5	35
3	60
3.8	90
4	110

The P_{min} values at intermediate M are interpolated from the above values

7.3. Pressure build-up characteristics

7.3.1. Effect of change of Mach no.

A_v (sft)	t (s)	q_{max} (psia)	M at q_{max}
0.7	5	12.71	2.06
0.85	4.5	15.40	2.06
1	4.13	18.09	2.06
1.5	3.17	27.33	2.39
2	2.7	37.32	2.01
2.5	1.23	45.40	1.73
3	1.8	50.74	1.62
3.5	1.0	54.50	1.56
4.2	0.71	58.00	1.50

It is noted from the table that if the PRV opening is not controlled, or if the PRV gets into a 'runaway' condition, the instantaneous q_{max} values can be very large, resulting in damage to model, balance etc.

7.3.2. Effect of rate of change of Mach no. for given valve area

In order to maximize the run time, it is required to change the Mach no. at the highest rate. Since P_{min} is a function of M, which in turn is a function of time, P_{min} also becomes a function of time. Considering **A,** of 0.7sft as shown in Figure 11, the effects of transition of M from 1.0 to 4.0 in 4s(dM/dt=0.75M/s), 3s(dM/dt=1.0M/s), and 2s(dM/dt=1.50M/s) are now discussed. Figure 15 show the P_{SC} build up and the P_{min} values for various rates of transition of M for A_v=0.7sft. It is observed that a rate faster than 0.75M/s results in insufficient P_{SC}. From several trials, it is noted that to achieve dM/dt=1 and 1.5M/s the minimum values of **A,** required are 0.85 and I, to ensure that at any instantaneous M, achieved P_{SC} is greater than P_{min}. However as indicated in Figure 16 and 17, for these conditions the achieved P_{SC} is much higher than P_{min}, resulting in a loss of useful time for testing at M=4.0. This calls for regulating the P_{SC} to a prescribed value in a pressure loop. Figure 18 shows the variation of q in the test section for various speeds of operation. Faster operation results in a higher magnitude of q_{max}. Table 3 summarizes the time required to reach 120 psia, q_{max} and M at q_{max} under various speeds of operation at the minimum PRV openings. It may be noted that high dM/dt causes increased q, which has a bearing on the model and balance design.

dM/dt (M/s)	Min A, (sft)	t (s)	q_{max} (psia)	M at q_{max}
0.75	0.7	5	12.71	2.06
1	0.85	J	13.93	I.92
1.5	I	3	16.55	1.75

7.3.3. Effect of higher starting Much no.

Starting M	Min A_v(sft)	*t* (s)	q_{max} (psia)	M at q_{max}
1.5	0.7	4.1	12.58	I .98
2	0.7	3.6	12.87	2
2.5	0.7	3	11.65	2.6

7.4. Run time pressure characteristics

The run time P_{SC} and the maximum run time available are influenced by the V_S a the drop in P_S. In the test facility, the air is stored in a series of five interconnect storage tanks of 25000cft capacity each and not all tanks may be available to t 0.6m tunnel. The effect of increased V_S from minimum (1 tank) to maximum tanks) is studied. P_{S0} has been taken as 163 psia though the tests can he done lower pressure also. Run time P_{SC} characteristics have been evaluated consideri M=1 at start with rate of change of 0.75M/s. For the present studies it is assum that the maximum run time would be up to the time P_S is higher than P_{SC} by 10% the P_{SC}.

7.4.1. Unregulated PR V

Figures 21 shows the variation in P_S for different V_S for A_v=0.7sft in the unregul mode of PRV (Figure 11). It is seen that the rate of P_S drop is higher during transition from Mach 1.0 to 4.0. Reduced P_S drop with increased V_S, as expect noted.

7.4.2. Regulated PRV

The control of PRV switches to the pressure mode when the pressure builds up to P_{SC}. For example if the P_{SC} builds up more than 120psia at M=4.0, the pressure mode will reduce the PRV area to maintain P_{SC} at 120psia. A typical PRV trajectory is shown in Figure 22. It is to be noted that the PRV opening gradually increases to compensate for the continuous drop in the P_S as the run advances. The parameters defined in Figure 22 for regulated PRV have been obtained by trial and error and are tabulated below for various numbers of storage tanks to buildup and maintain the constant P_{SC} of 120psia at M=4.0.

Table *6*

No.of Storage tanks	A_{v1} (sft)	t_1 (s)	A_{v2} (sft)	dt (s)	dA_v/dt (sft/s)	Maximum runtime (s)
1	0.7	4.9	0.41	0.2	0.0096	11
2	0.7	4.9	0.34	0.2	0.0044	30
3	0.7	4.9	0.32	0.2	0.0024	55
4	0.7	4.9	0.32	0.2	0.0016	80
5	0.7	4.9	0.32	0.2	0.0012	100

The P_{SC} along with P_S drop and the M variation for one and two storage tanks are shown in Figures 23 and 24 respectively. The typical runtime proposed in VMFN operation is 30s and maximum proposed is 120s. The results show that for runtime of 30s one tank would not be sufficient.

7.5. Pressure drop characteristics

7.5.1. Effect of change of Mach no.

The PRV is set to start closing simultaneously as the nozzle contour is changed from Mach 4.0 to 1.0 at the rate of 0.75 M/s after completion of the test. The P_{SC} characteristics for different rates of closing the PRV are shown in Figure 25. It is seen that the P_{SC} is always above the P_{min} irrespective of PRV closing rate. The P_{SC} drops to the P_{atm} in about 3s.

The effect of changing from Mach 4.0 to 1.0 on **q** is shown in Figure 26 for the previous PRV closing rates. It is seen that the **q** peaks to a high value, q_{max} during transition from Mach 4.0 to 1.0 during stopping also. The q_{max} is higher than that during starting of the run. Higher closing rate causes a marginal reduction in q_{max} but at a marginally higher M. The time for the P_{SC} to drop to ambient, q_{max} and the M at q_{max} are tabulated below for various rates of closing the PRV

dA_v/dt (sft/s)	**t (s)**	**q_{max} (psia)**	**M at q_{max}**
0.0875	**3**	16.42	2.78
0.1167	3	15.83	2.82
0.1750	3	14.83	2.93

7.5.2. Effect of rnte of change of Much no. for given valve urea

For various speeds of change from M=4 to 1, the P_{SC} drop Characteristics are shown in Figure 27. The P_{SC} drops significantly faster as dM/dt increases. The instantaneous pressure at any M is also above P_{min} for all dM/dt. The q characteristics (Figure **28)** show the occurrence of q_{max} of as much as 30psia when M is changed to 1.0 at the rate of 3M/s.The results are tabulated below.

dM/dt (M/s)	**t (s)**	**q_{max} (psia)**	**M at q_{max}**
1	2.5	18.84	2.57
1.5	2	22.86	2.31
3	1.5	30.80	1.90

7.5.3. Effect of higher stopping Mach no.

The effect of stopping at higher M is studied. The P_{SC} drop characteristics are considered by changing the Mach no. at the rate of 0.75M/s, as the PRV is simultaneously closed at the rate of 0.0875sft/s. The results are shown in Figure 27. It is seen that, the P_{SC} drop characteristics do not change with the higher stopping M. The effect on q is shown in Figure 28. Again, it can be noted that the q_{max} does not change as well as M at q_{max}. The results are tabulated below.

Stopping M	dM/dt (M/s)	t (s)	q_{max} (psia)	M at q_{max}
1.5	0.75	3	16.42	2.78
2	0.75	3	16.42	2.78
2.5	0.75	3	16.42	2.78

8. Concluding remarks

Predictions of the P_{SC} characteristics for VMFN operation in 0.6m wind tunnel are presented. The predictions are validated with experimental data from 0.6m wind tunnel at subsonic M. The simulation has been used to predict the PRV opening trajectory necessary to maintain P_{SC} above P_{min} value required to maintain the supersonic flow in the test section at any M. During transition from M=1.0 to M=4.0 and vice versa, peak values of q of as much as 30psia are indicated. Thus it appears that even though the use of VMFN may alleviate start stop loads. the need to design wind tunnel models for loads arising from high q still continues

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2. **Anderson, John D., Jr,** ***Modern Compressible Flow: with Historical Perspective,*** McGraw-Hill Book Co., **New** York, *1982.*

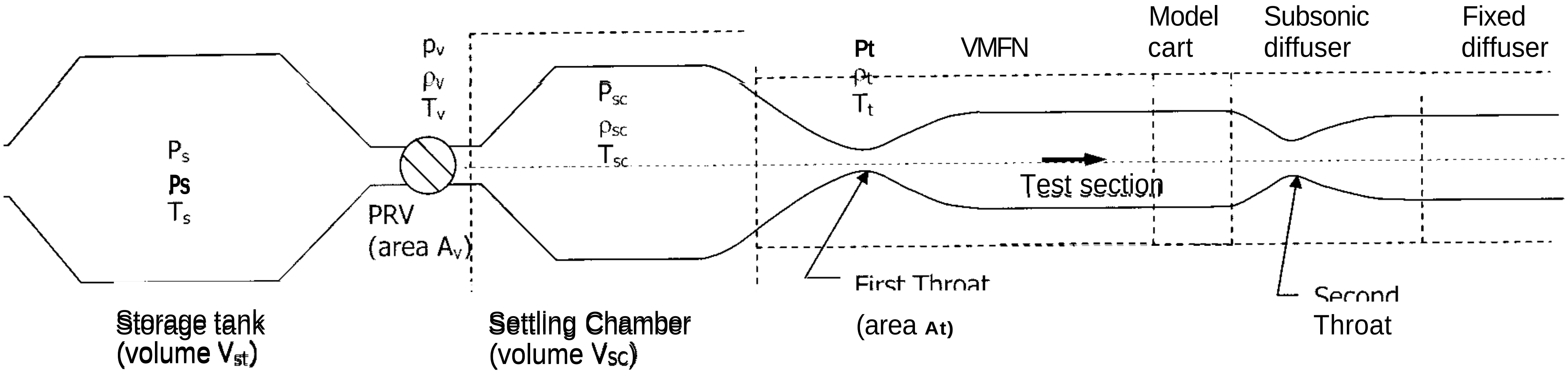

Figure 1. Schematic of 0.6m wind tunnel with VMFN

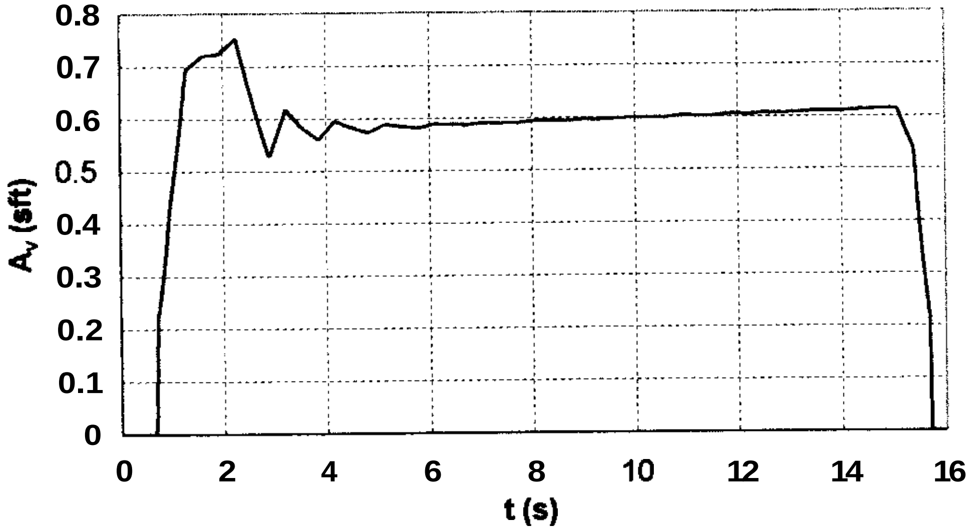

Figure 2. Valve opening trajectory for M = 0.2

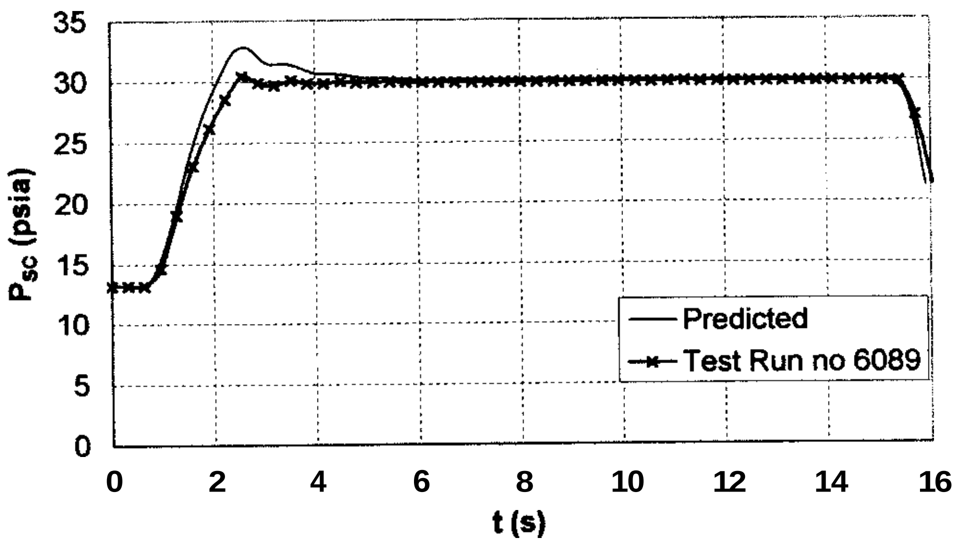

Figure 3. Comparison of experimental results of P_{SC} with theoritical prediction for M = 0.2

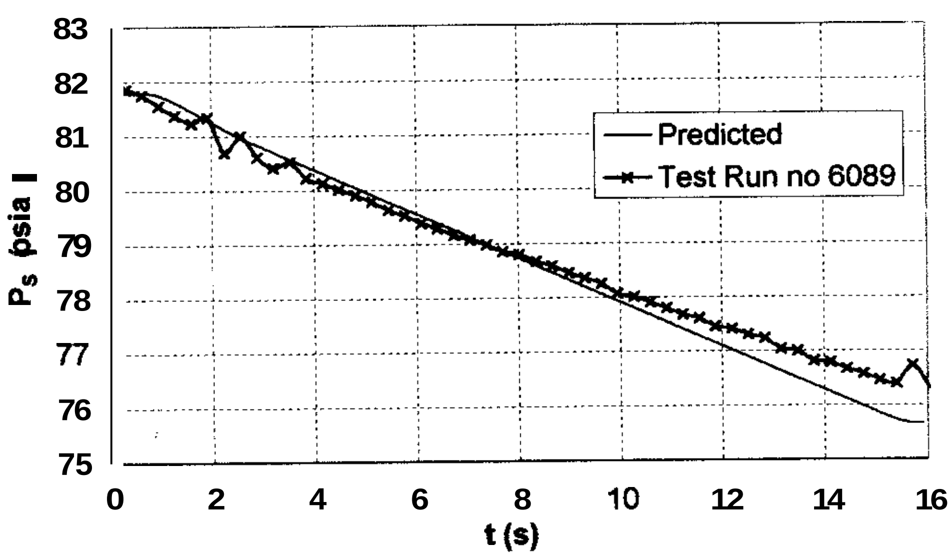

Figure 4. Comparison of experimental results of P_S with theoritical prediction for M = 0.2

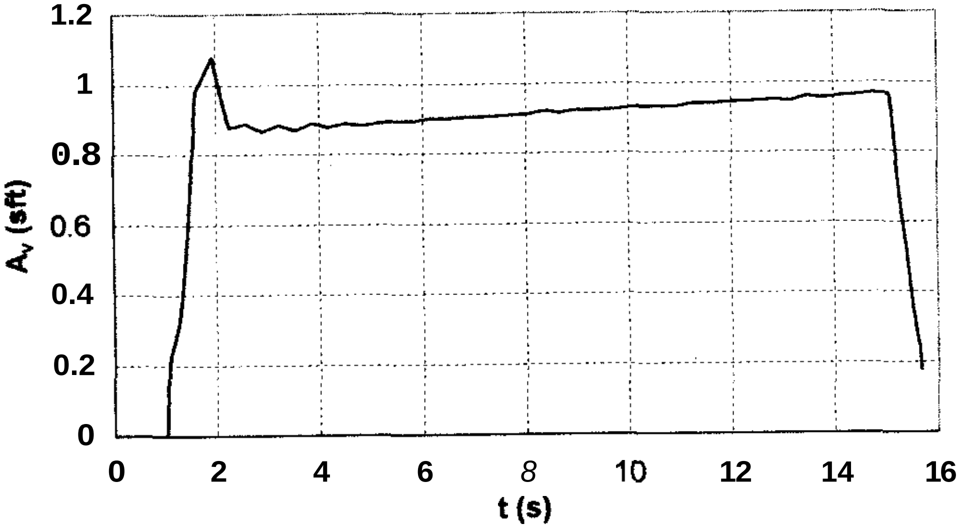

Figure 5. Valve opening trajectory for M = 0.5

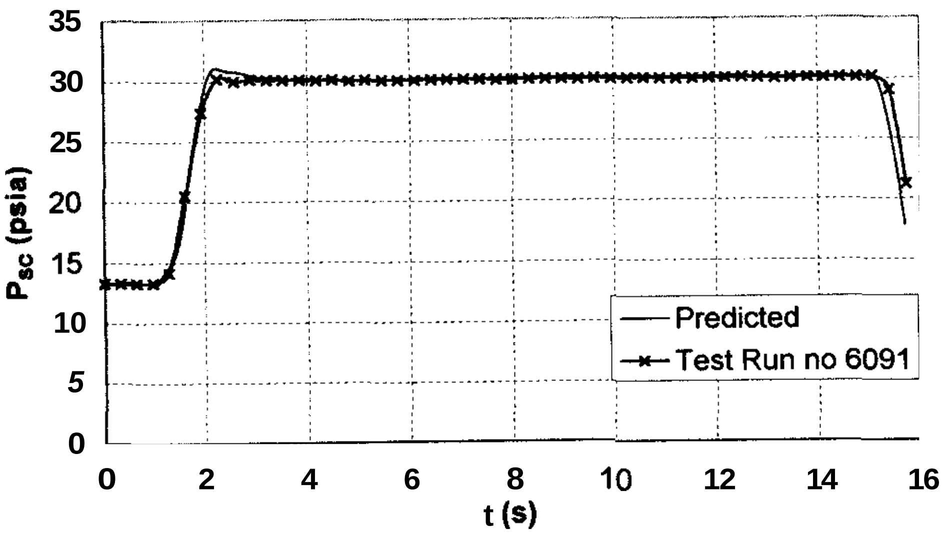

Figure **6. Comparison of experimental results of P_{SC} with theoritical prediction for M=0.5**

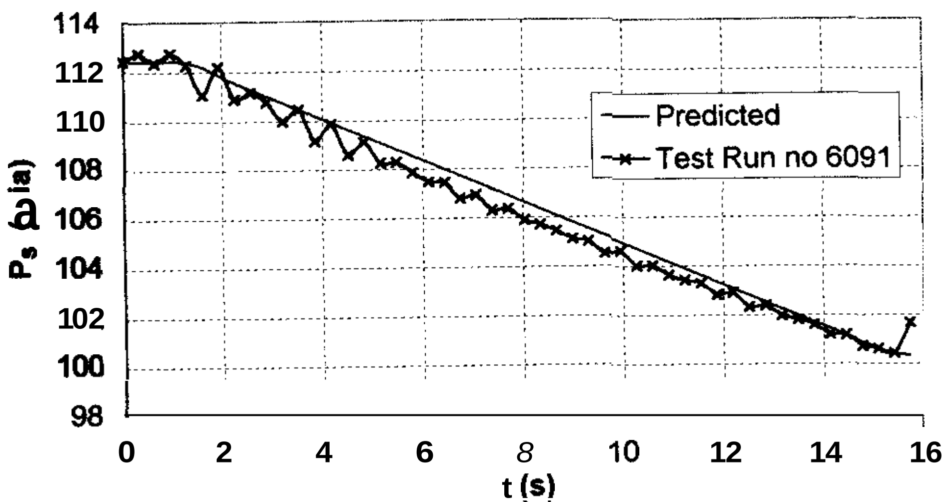

Figure 7. Comparison of experimental results of P_S with theoritical prediction for M = 0.5

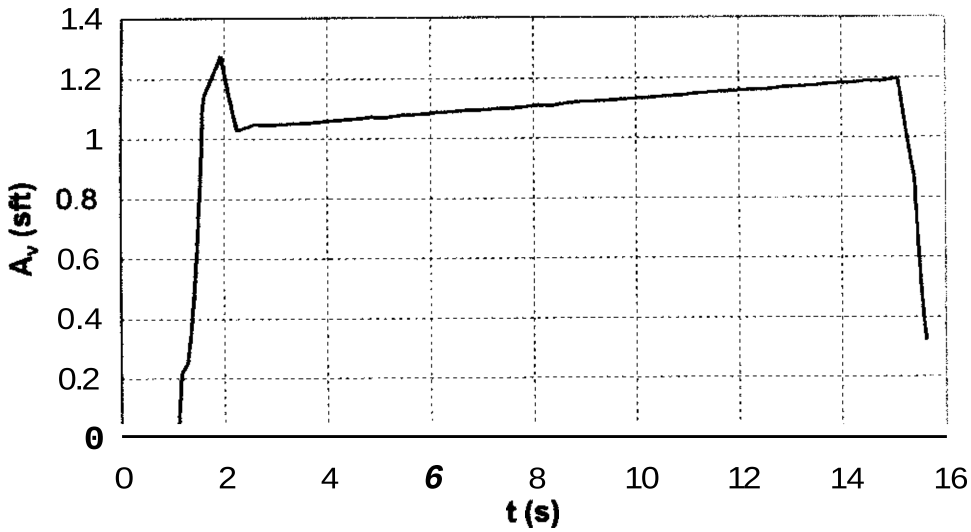

Figure 8. Valve opening trajectory for M = 0.6

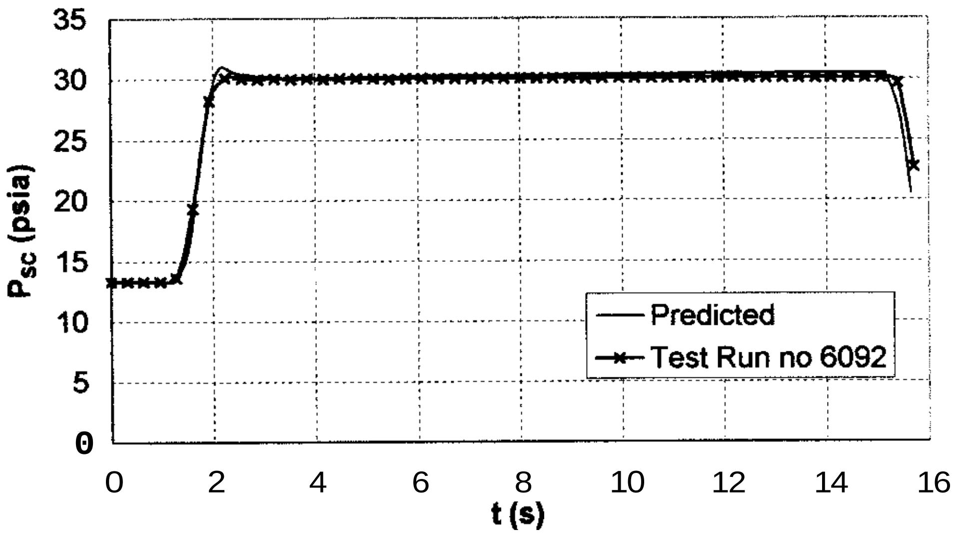

Figure 9. Comparison of experimental results of P_{SC} with theontical prediction for M = 0.6

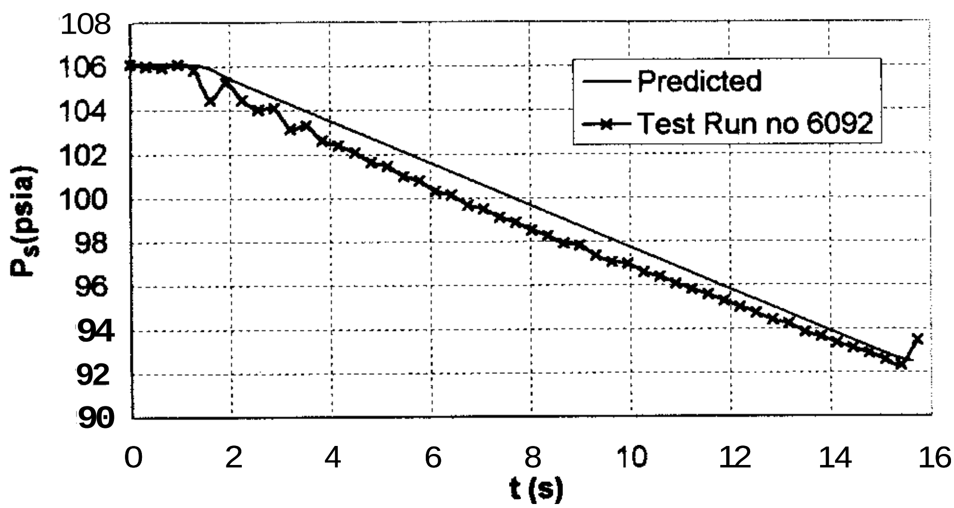

Figure 10. Comparison of experimental results of P_S with theontical prediction for M = 0.6

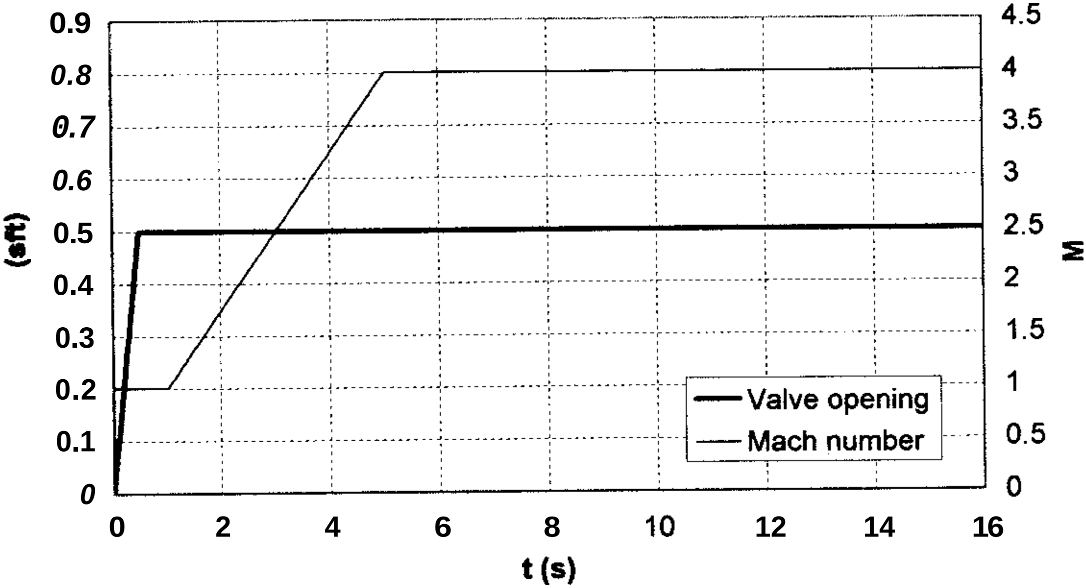

Figure 11. Inputs of PRV trajectory and Mach number profile

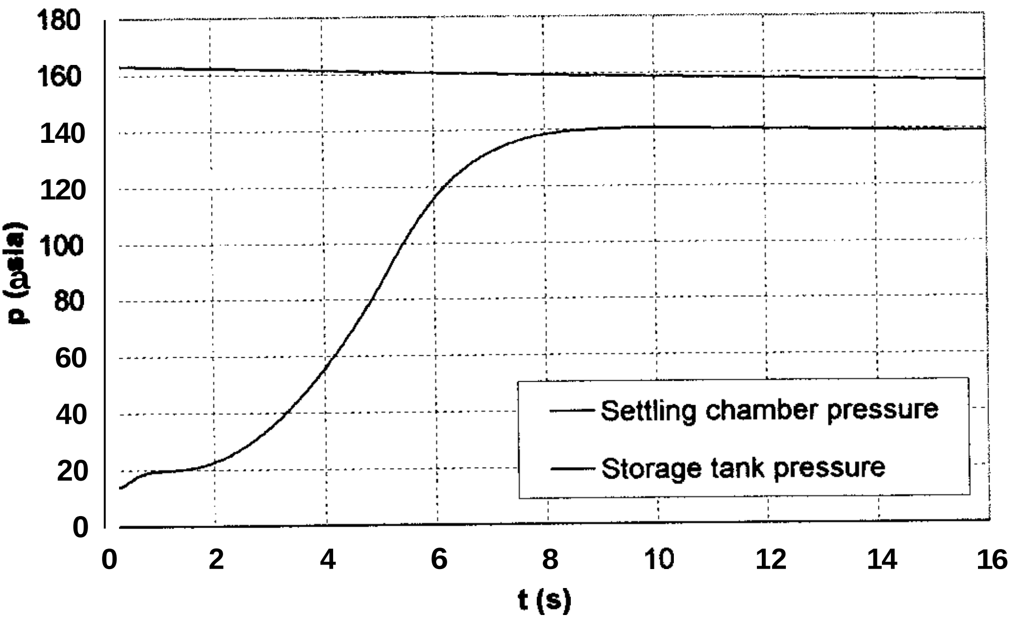

Figure 12, Effect of change of nozzle throat on P_{SC} buildup

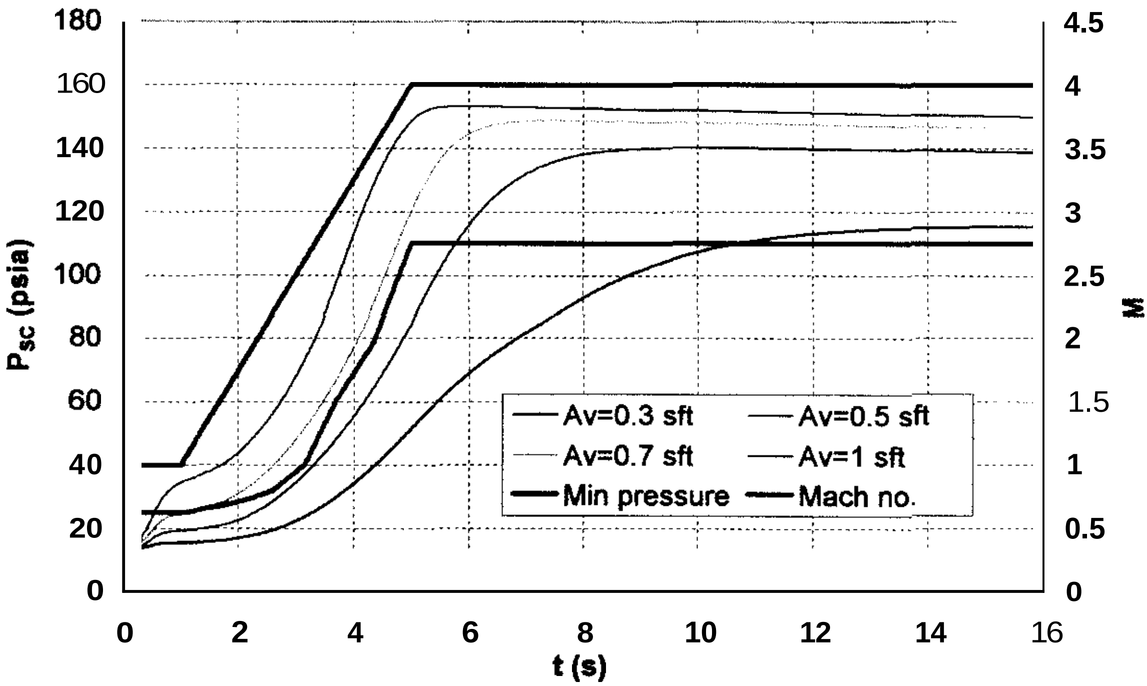

Figure 13. Effect of change of M on buildup of P_{SC} for some A,

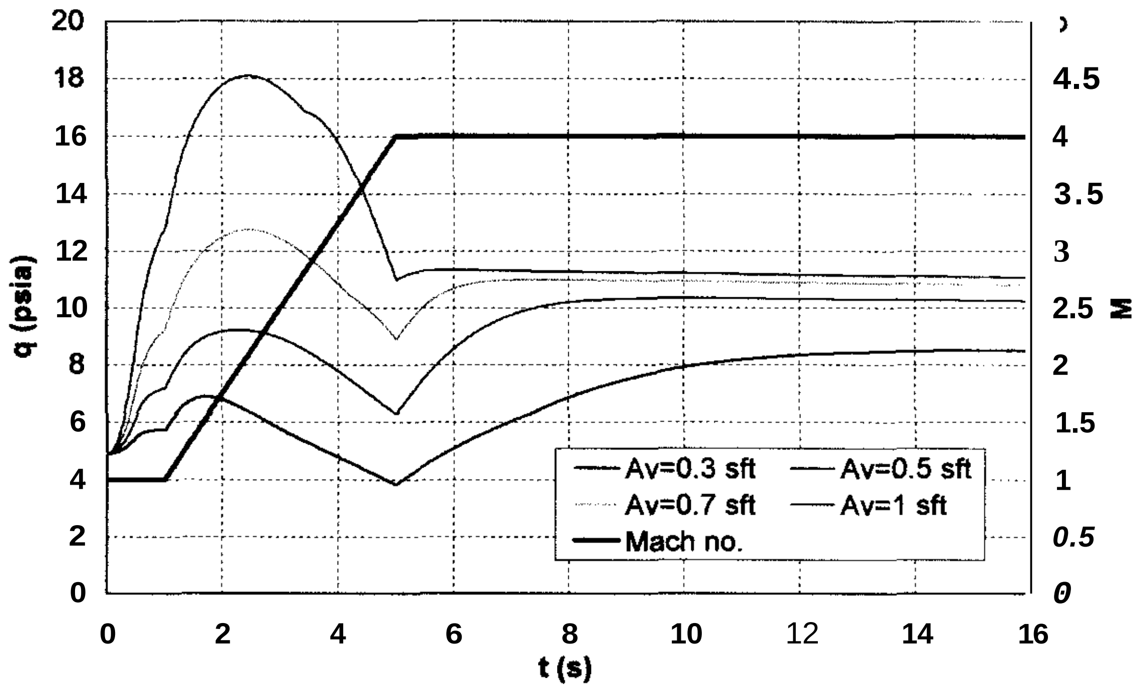

Figure 14. Effect of change of M on q for some A_v

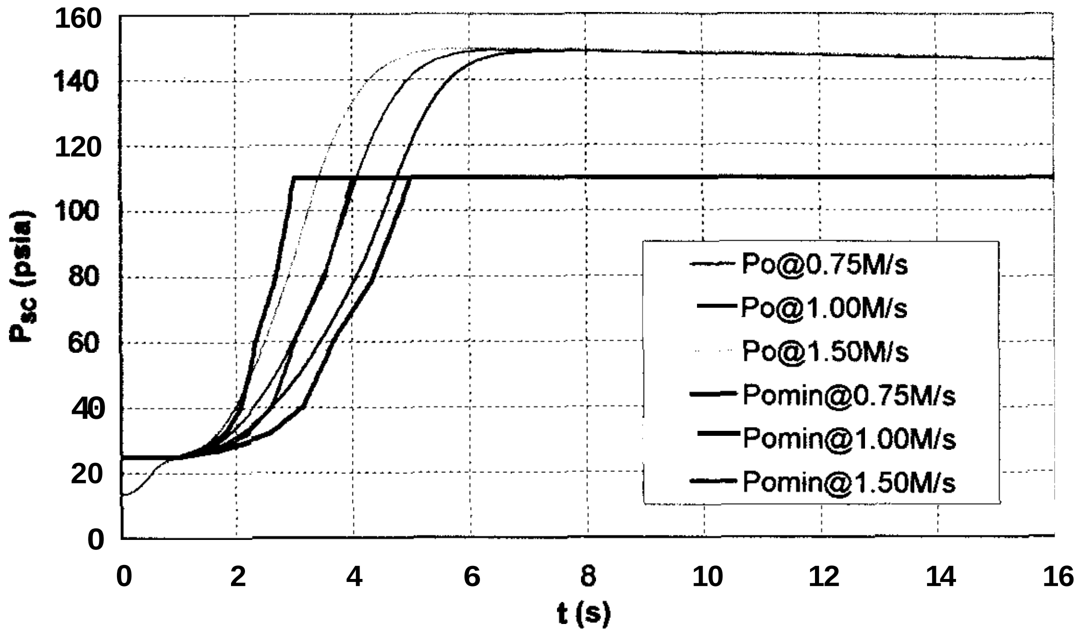

Figure 15. Effect of dM/dt on buildup of P_{SC} for A_v=0.7sft

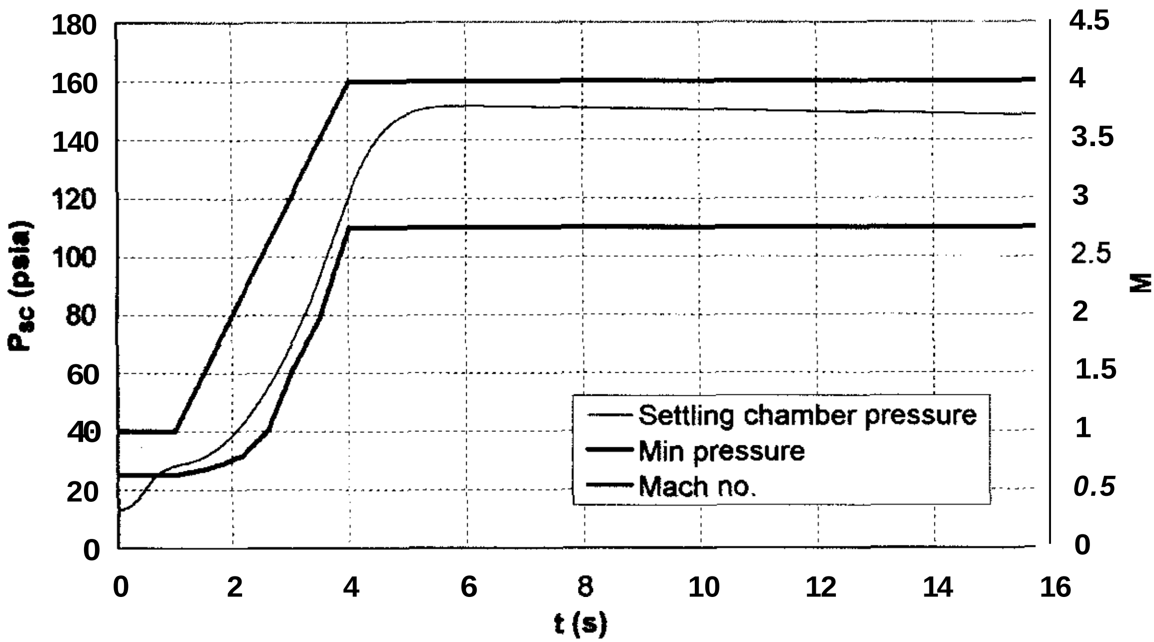

Figure 16. P_{SC} buildup for dM/dt=1M/s and Av=0.85 sft

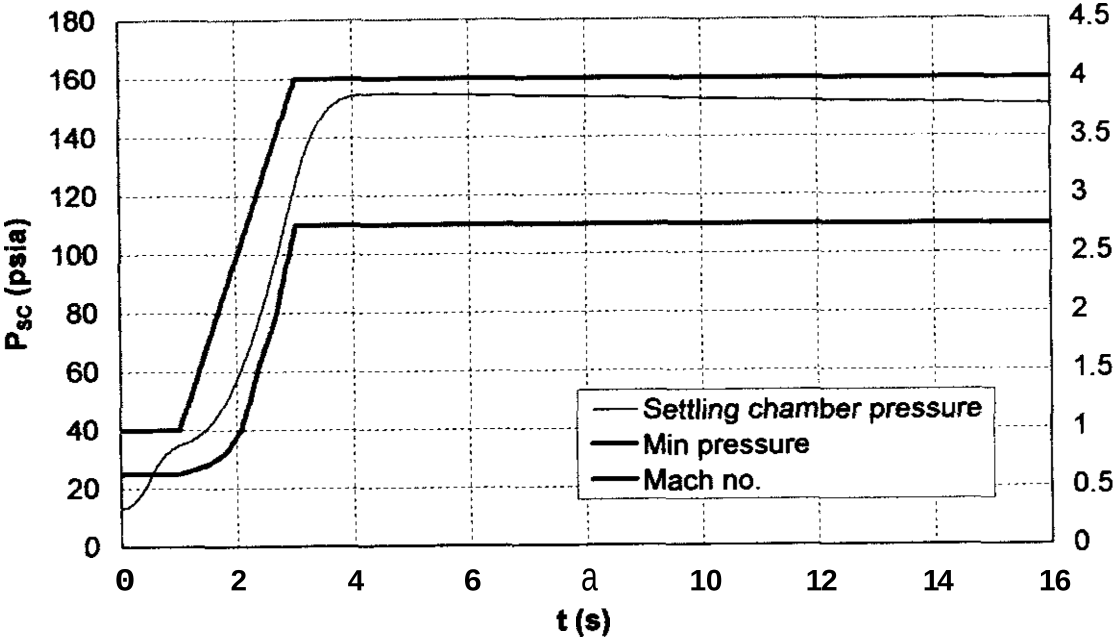

Figure 17. P_{SC} buildup for dM/dt=1.5M/s and Av=1sft

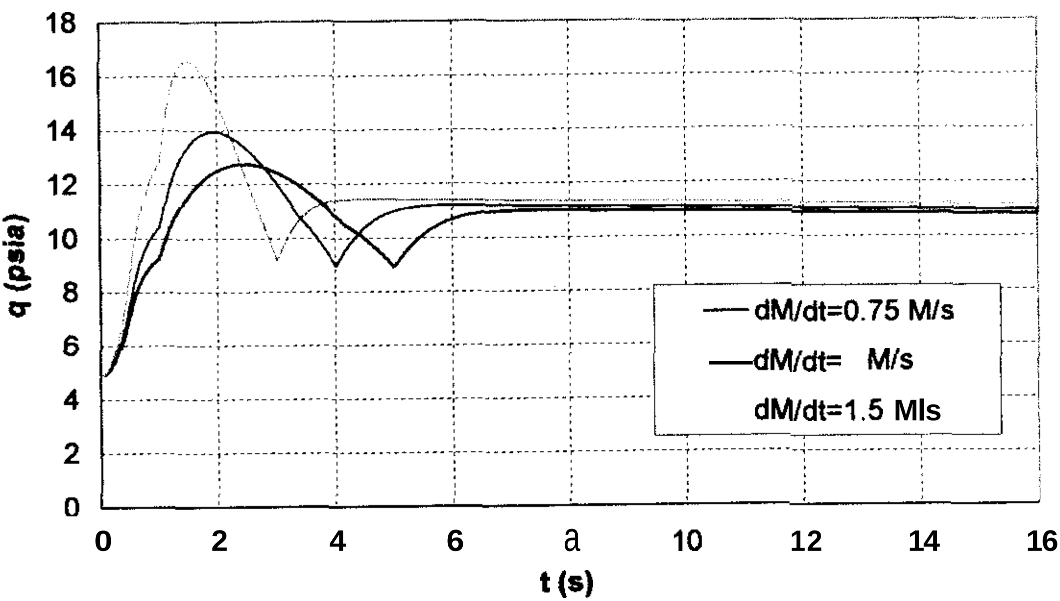

Figure 18. Effect of dM/dt on q

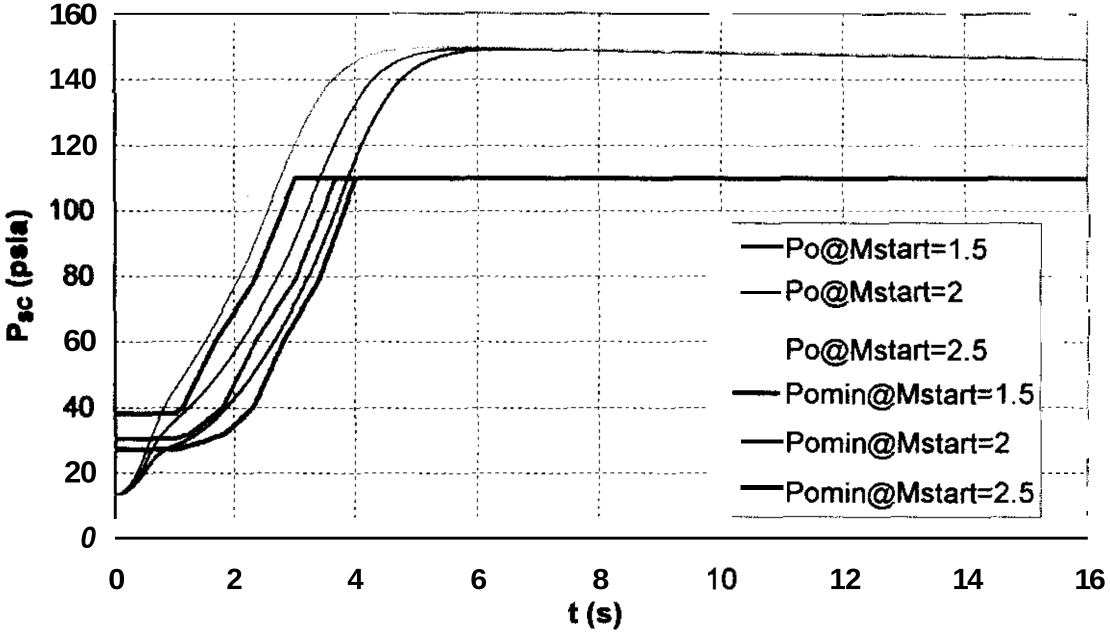

Figure 19. Effect of higher starting M on P_{SC} buildup

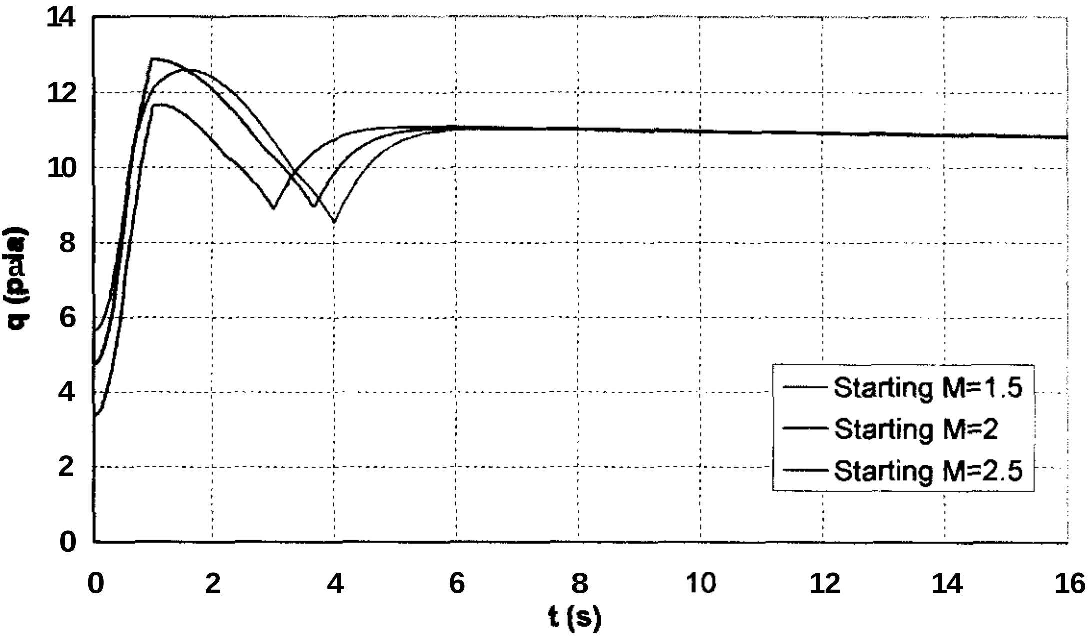

Figure 20. Effect of higher starting M on q

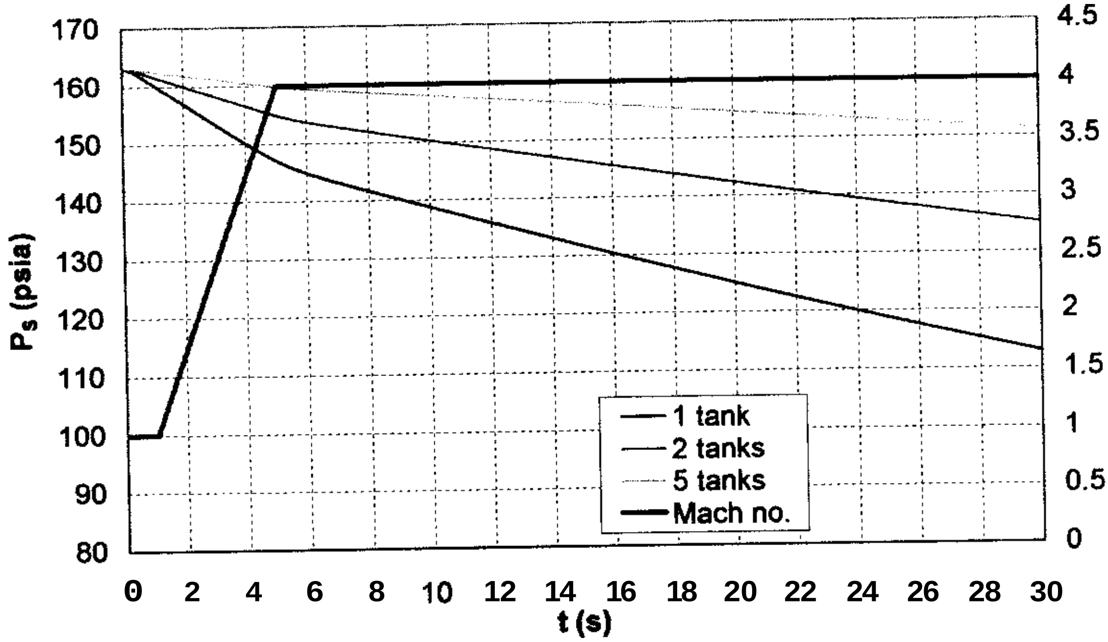

Figure 21. Effect of V_S on drop in P_S

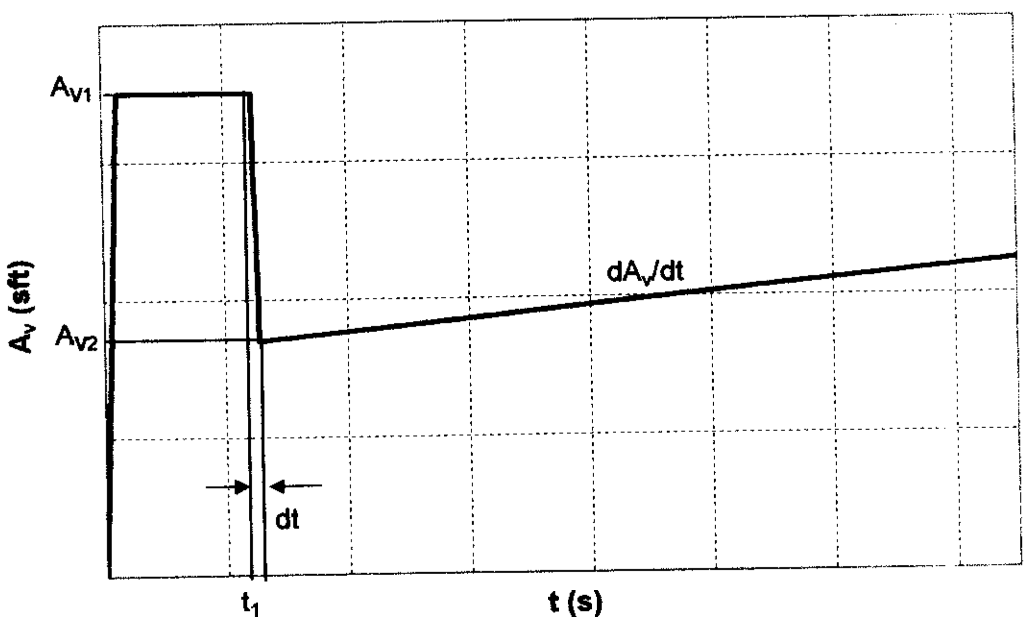

Figure 22. Typical A_v trajectory in regulated mode

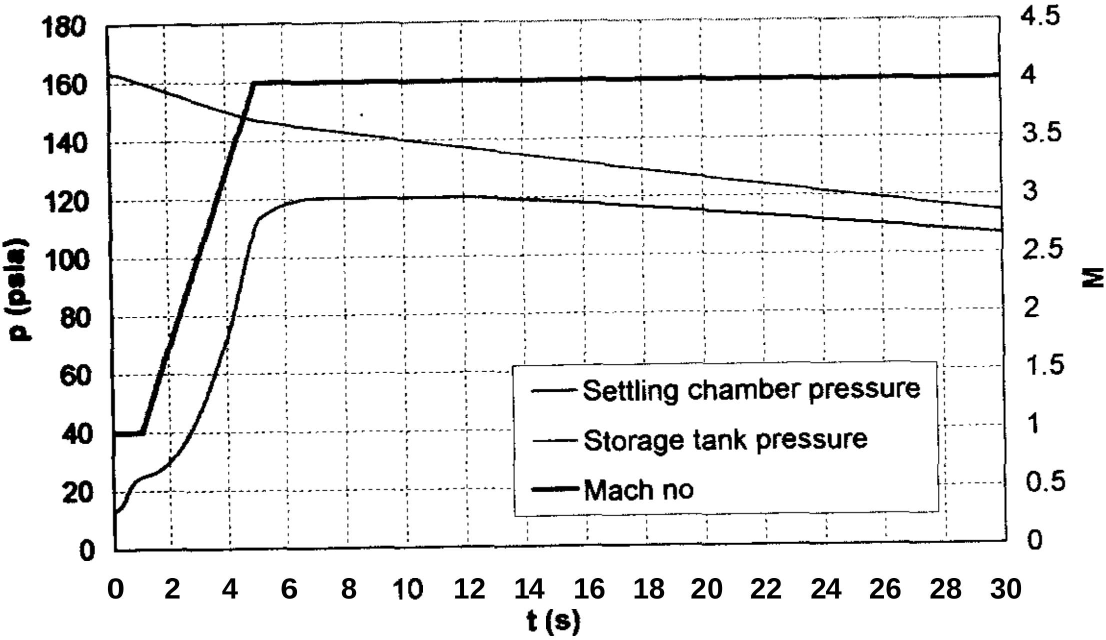

Figure 23. P_{SC} and P_S in regulated mode of PRV for one storage tank

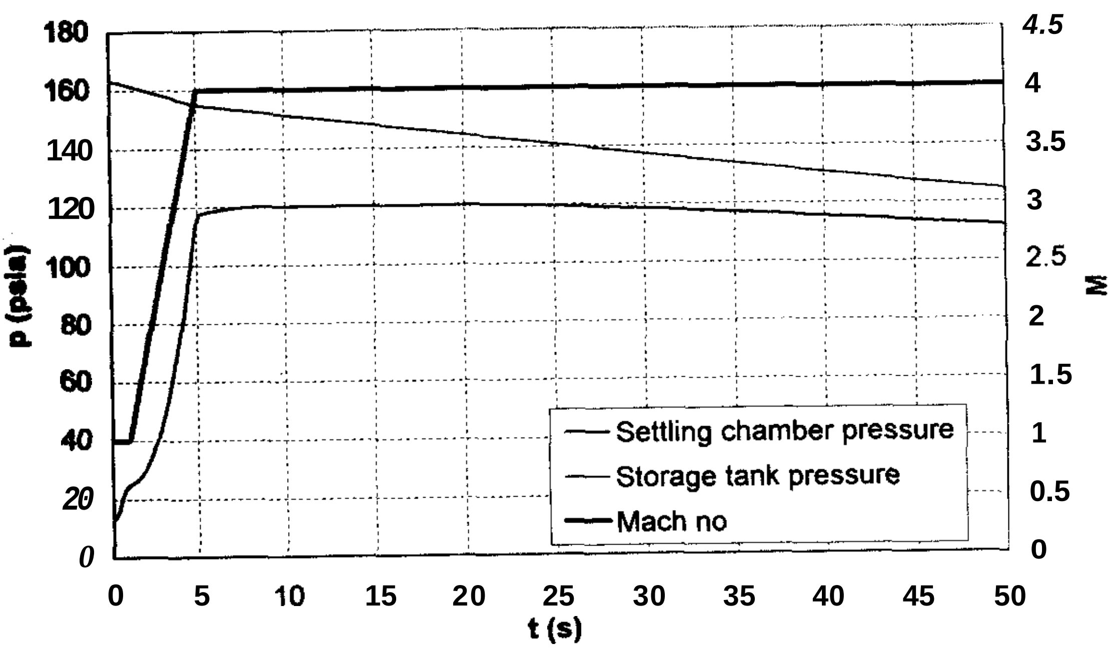

Figure 24. P_{SC} and P_S in regulated mode of PRV for two storage tanks

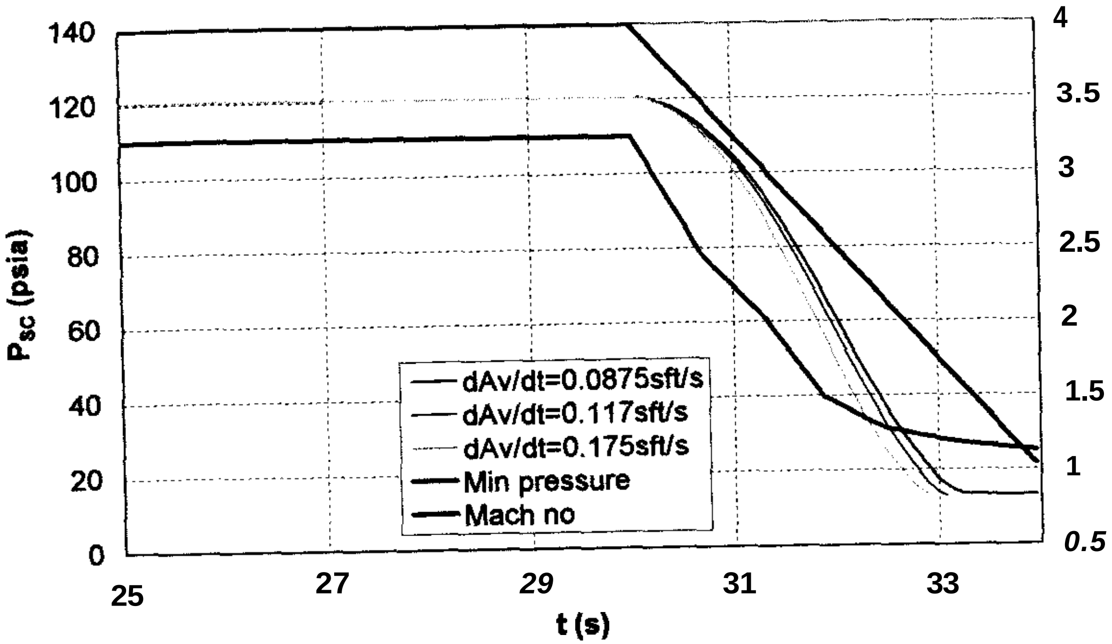

Figure 25. Effect of change of M from 4.0 to 1.0 on P_{SC} drop characteristics for some rates of closing the PRV

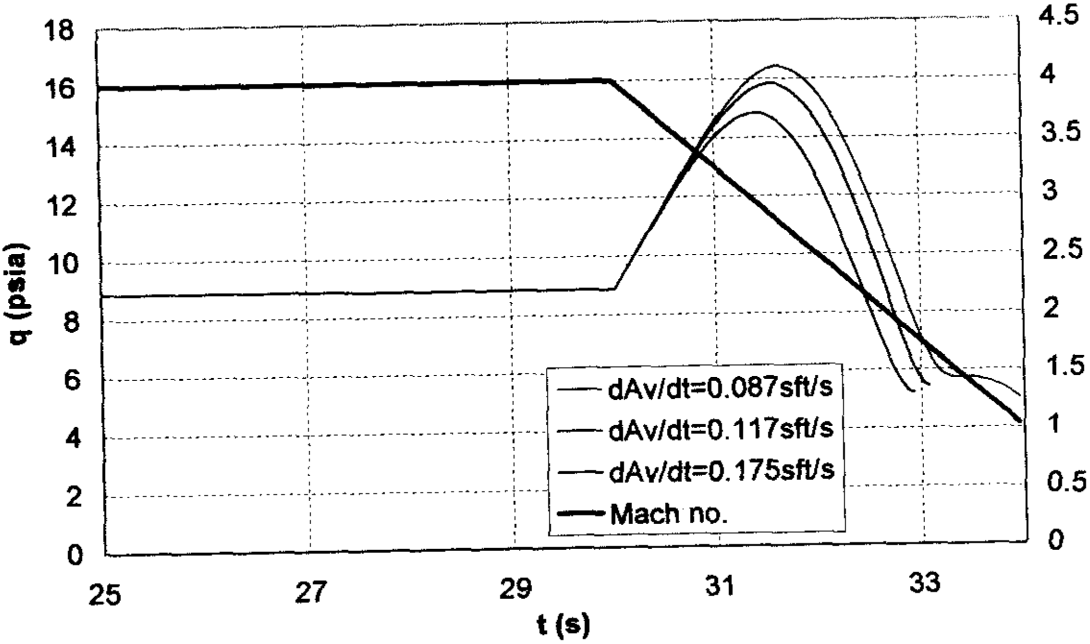

Figure 26. Effect of change of M from 4.0 to 1.0 on q for some rates of closing the PRV

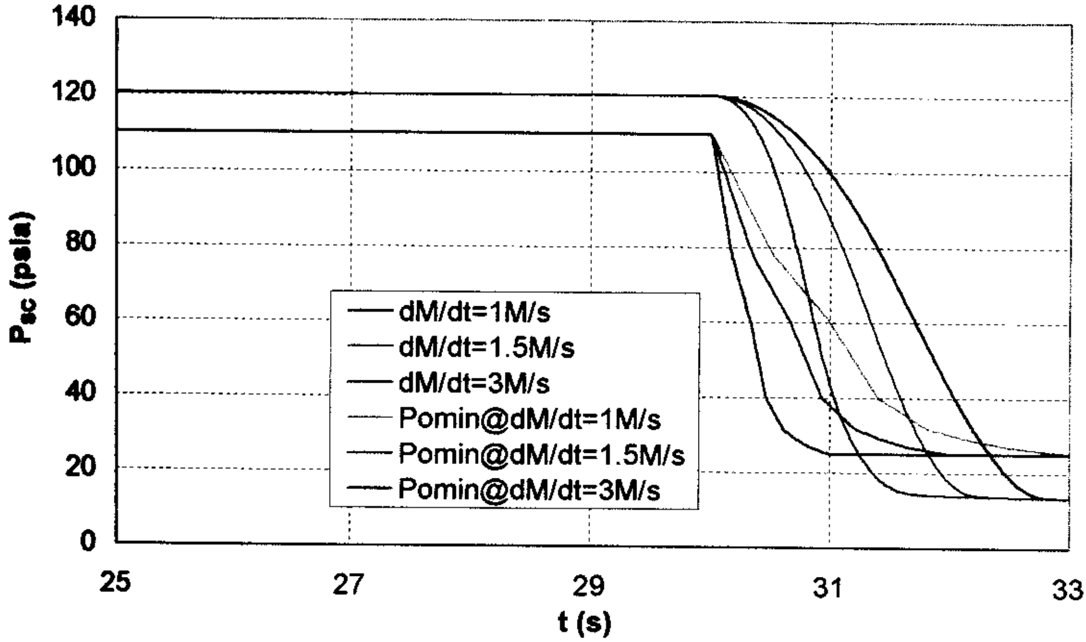

Figure 27. Effect of dM/dt on P_{SC} drop characteristics

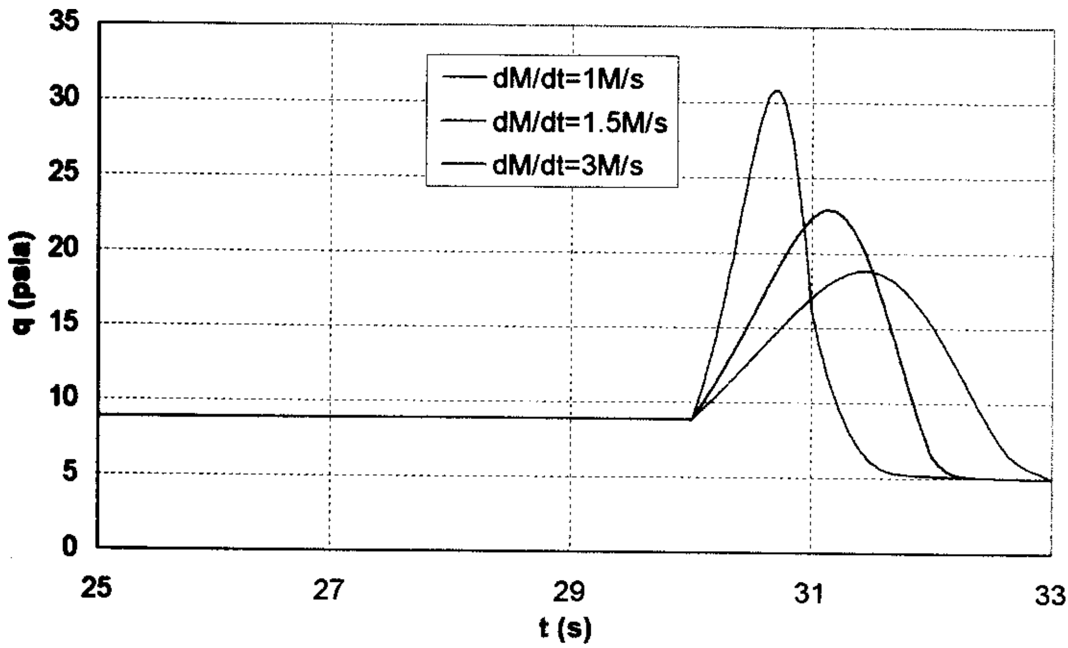

Figure 28. Effect of dM/dt on q

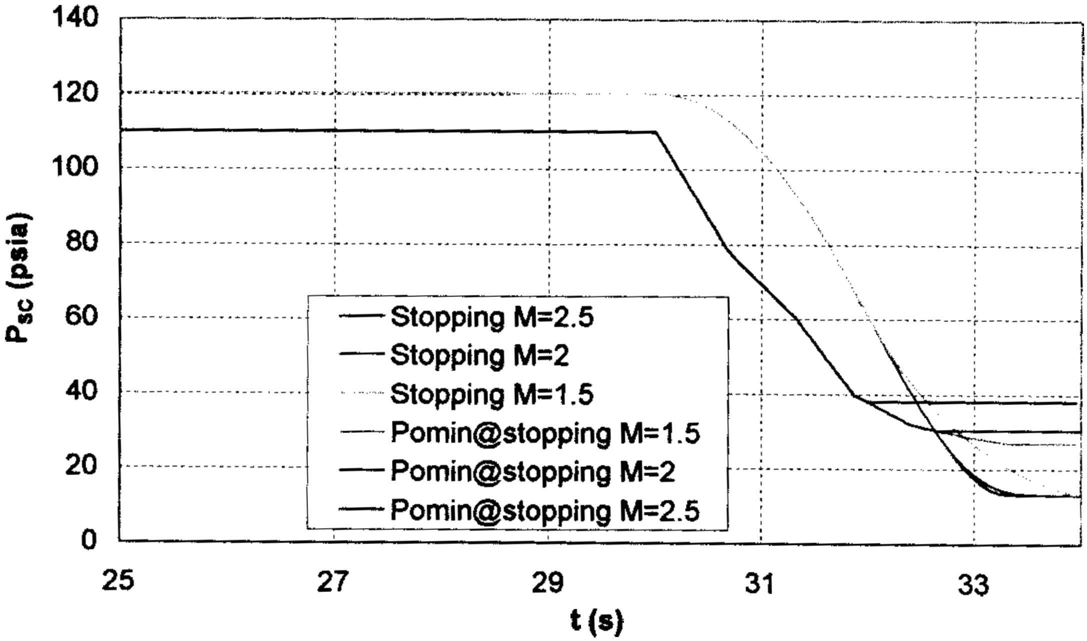

Figure 29. Effect of higher stopping M on P_{SC} drop characteristics

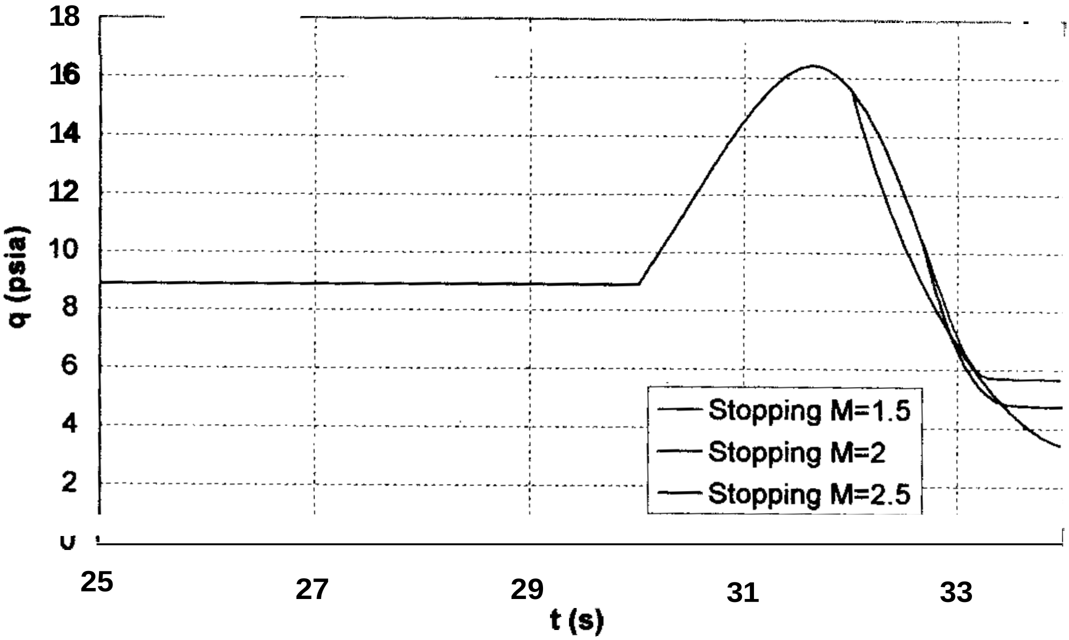

Figure 30. Effect of higher stopping M on q

Appendix A: Program listing

```
/* Settling chamber pressure buildup characteristics
Input parameters:
Storage tank volume Vs
Senling chamber volume Vsc
expansion index n
initial storage tank pressure Pso
atmospheric pressure Patm
ratio of specificheats gamma=1.4
valve opening trajectories (Avi), (Avi,tm),(Avi1,t1,Avi2, t2,t3)
Av=4.305sft
gas constant R
initial storage tank temperature Tso
test section area Ainf=4
test section mach number Minf
ambient temperature Tinf
*/

#include<stdio.h>
#include<stdlib.h>
#include<math.h>
#include<conio.h>

float F1(float,float,float,float,float,float,float,float,float,float);
float F2(float, float,float,float,float,float);
float F3(float,float,float,float,float,float,float,float,float,float);
float F4(float,float,float,float,float,float);
float Av(float);
float stroke(float,float);
float Pmin(float);
float M(float,float);

void main()
{

float Vsc,Vs,Vr;
float n,Patm,Tso,gamma,R;
float Ainf,At,Ar;
float C1,C,C2;
float rt,frt1,frt2,frt3,frt4,frt,Frt,rv,frv1,frv2,frv3,frv4,frv,Frv;
float Avi1,Avi;
float Pso,Pscbar,delPscbar;
float K1,K2,K3,K4,K5,K6,K7,K8;
int choke;
float K11,K12,K13,K14,K21,K22,K23,K24;
float Psbar,delPsbar;
float tstar,tau,t,delt,deltau;
float Tmax;
float g1,g2,g3,g4;
float Mts,Minf;
float q,Ps,Ae;
float facloss=1;
floats;

FILE *data=fopen("data.txt","w");

printf("Enter Minf : ");
```

```
scanf("%f",&Minf);

Pso=163;
Patm=13.2;
Vs=25000;
n=1.2;
gamma=1.4;
Tso=546;
Ainf=4;
R=1707;
Avi1=1;

g1=3;
g2=3.5;
g3=1.4286;
g4=0.2857;

C1=0.578703;
C=0.528282;

if(Minf>1.2)
Vsc=900;
else
Vsc=1000;
Vr=Vsc/Vs;

tstar=Vs/(Avi1*sqrt(gamma*R*Tso));

Pscbar=Patm/Pso;
Psbar=1;

delt=0.025;
deltau=delt/tstar;
Tmax=30;

for(t=0;t<=Tmax;t=t+delt)
{
Mts=M(t,Minf);
C2=1+0.2*Mts*Mts;
Ps = Pscbar*Pso/pow(C2,3.5);
q = 0.7*Ps*Mts*Mts;
s=pow(C2,g1);
tau=t/tstar;
Avi=Av(stroke(tau,tstar));
At=Ainf*Mts/(C1*s);
Ar=At/Avi1;

fprintf(data,"%f %f %f %f %f %f %f %f %d
\n",t,Pscbar*Pso,Psbar*Pso,q,Mts,Ainf/At,Avi,Pmin(Mts),choke);

if(0.95*Pscbar/Psbar<=C)
choke=1;

else
{
choke=0;
rv=0.95*Pscbar/Psbar;
frv1=5;
frv2=pow(rv,g3);
frv3=pow(rv,g4);
```

```
frv4=(1-frv3);
frv=sqrt(frv1*frv2*frv4);
Frv=frv;
}

if((Patm/Pso)/(Pscbar)>C)
{
rt=(Patm/Pso)/(Pscbar);
frt1=5;
frt2=pow(rt,g3);
frt3=pow(rt,g4);
frt4=(1-frt3);
frt=sqrt(frt1*frt2*frt4);
Frt=frt;
facloss=0.95;
}

else
I
facloss=1;
Frt=C1;
}


/*************VALVE CHOKED***********/
if(choke==1)
{
K5=F4(tau,Psbar,n,C1,Avi1,tstar)*deltau;
K6=F4(tau+0.5*deltau,Psbar+0.5*K5,n,C1,Avi1,tstar)*deltau;
K7=F4(tau+0.5*deltau,Psbar+0.5*K6,n,C1,Avi1,tstar)*deltau;
K8=F4(tau+deltau,Psbar+K7,n,C1,Avi1,tstar)*deltau;

K1=F1(tau,Pscbar,Psbar,C1,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;
K2=F1(tau+0.5*deltau,Pscbar+0.5*K1,Psbar+0.5*K5,C1,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;
K3=F1(tau+0.5*deltau,Pscbar+0.5*K2,Psbar+0.5*K6,C1,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;
K4=F1(tau+deltau,Pscbar+K3,Psbar+K7,C1,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;

delPscbar=(K1+2*K2+2*K3+K4)/6;
Pscbar=Pscbar+delPscbar;

delPsbar=(K5+2*K6+2*K7+K8)/6;
Psbar=Psbar+delPsbar;
}


/*************VALVE UNCHOKED***********/
if(choke==0)
{
K11=F2(tau,Psbar,n,Frv,Avi1,tstar)*deltau;

K21=F3(tau,Psbar,Pscbar,Frv,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;

K12=F2(tau+0.5*deltau,Psbar+0.5*K11,n,Frv,Avi1,tstar)*deltau;

K22=F3(tau+0.5*deltau,Psbar+0.5*K11,Pscbar+0.5*K21,Frv,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;

K13=F2(tau+0.5*deltau,Psbar+0.5*K12,n,Frv,Avi1,tstar)*deltau;

K23=F3(tau+0.5*deltau,Psbar+0.5*K12,Pscbar+0.5*K22,Frv,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;
```

```
K14=F2(tau+deltau,Psbar+K13,n,Frv,Avi1,tstar)*deltau;

K24=F3(tau+deltau,Psbar+K13,Pscbar+K23,Frv,Vr,Ar,Frt,Avi1,tstar,facloss)*deltau;

delPsbar=(K11+2*K12+2*K13+K14)/6;
delPscbar=(K21+2*K22+2*K23+K24)/6;
Psbar=Psbar+delPsbar;
Pscbar=Pscbar+delPscbar;
}
}

fclose (data);
}



float F1(float tau. float Pscbar,float Psbar,float C1,float Vr,float Ar,float Frt. float Avi1,float
tstar,float facloss)
{
return (Psbar*Av(stroke(tau,tstar))*C1/Avi1-Ar*facloss*Pscbar*Frt)/Vr;
}

float F2(float tau. float Psbar.float n,float Frv,float Avi1,float tstar)

float g1;
g1 =(2*n-1)/n;
return (-1)*n*Frv*pow(Psbar,g1)*Av(stroke(tau,tstar))/Avi1 ;
}


float F3(float tau, float Psbar,float Pscbar,float Frv,float Vr,float Ar, float Frt,float Avi1,float
tstar,float facloss)
{
return (Psbar*Av(stroke(tau,tstar))*Frv/Avi1-Ar*facloss*Pscbar*Frt)/Vr;
}


float F4(float tau,float Psbar,float n, float C1,float Avi1,float tstar)
{
float g1;
g1 = (2*n-1)/n;
return -n*C1*pow(Psbar,g1)*Av(stroke(tau,tstar))/Avi1;
}


float Pmin(float M)

if(M<=1)
return 25;
else if(M<=1.5254)
return 25+(27.0337-25)/0.5254*(M-1),
else if(M<=1.8543)
return 27.0337+(29.089-27.0337)/0.3289*(M-1.5254);
else if(M<=2.19)
return 29.089+(31.9-29.089)/0.3357*(M-1.8543);
else if(M<=2.5912)
return 31.9+(39.56-31.59)/0.4012*(M-2.19);
else if(M<=3.0109)
return 39.56+(60.4-39.56)/0.4197*(M-2.5912);
else if(M<=3.4862)
```

```
return 60.54+(78.2325-60.54)/0.4753*(M-3.0109);
else if(M<4)
return 78.2325+(110-78.2325)/0.5138*(M-3.4862);
else
return 110;
}

float stroke(float tau,float tstar)
{
FILE *input1=fopen("prvpos.txt","r");
FILE *input2=fopen("prvpos.txt","r");

float t,t1,t2,t3=0,Av1,Av2,Av3=0;
t=tau*tstar;

do
fscanf(input1,"%f\t%f\n",&t2,&Av2);
while(t2<=t);
fclose(input1);

do
{
t1=t3;
Av1=Av3;
fscanf(input2,"%f\t%f\n",&t3,&Av3);
}
while(t3<=t);
fclose(inpuf.2);

return Av1+(Av2-Av1)*(t-t1)/(t2-t1);
}

float Av(float stroke)
{
/*FILE *input1=fopen("stroke.txt","r");
FILE *input2=fopen("stroke.txt","r");

float t,t1,t2,t3=0,Av1,Av2,Av3=0;

t=stroke;

do
fscanf(input1,"%f\t%f\n",&t2,&Av2);
while(t2<=t);
fclose(input1);

do
{
t1=t3;
Av1=Av3;
fscanf(input2."%f\t%f\n".&t3.&Av3);
}
while(t3<=t);
fclose(input2);

return Av1+(Av2-Av1)*(t-t1)/(t2-t1);*/return stroke:
}

float M(float t,float Minf)
{
```

```
if(t<=1)
return 3;
else if(t<=2.3333)
return 3+1*(t-1)/1.3333;
else if (t<=24)
return Minf;
else if(t<=28)
return 4-3*(t-24)/4;
else
return 1;
}
```

Documentation Sheet

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Title	Prediction of Pressure Characteristics in Settling Chamber of 0.6m Wind Tunnel for supersonic testing
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Abstract

It is proposed to augment the NAL 0.6m wind tunnel with a Variable Mach number Flexible Nozzle (VMFN) enhance the testing capability from transonic to supersonic Mach numbers (up to 4.0). In order to avoid the start stop lo that are inherent in blow down wind tunnels, it is proposed to start the tunnel at a low Mach number (say 1.0) and th increasing the Mach number by reducing the nozzle throat (maximum Mach number = 4.0) by continuously flexing t nozzle walls; the reverse process is to be adopted while stopping. In such an operation, two important issues arise. Firs the settling chamber pressure should always be maintained above the minimum 'running' pressure at any supersonic Ma number to avoid flow breakdown in the test section. Secondly, in order to maintain the free-stream dynamic pres constant during the useful runtime and within desirable limits during the transition from Mach 1.0 to 4.0 and vice versa, t Pressure Regulating Valve (PRV) must be operated in a closed - loop pressure control. In this report, the problem formulated based on assumptions of quasi-steady isentropic equations and a program is presented in C language to study t nature of variation of stagnation pressure in the settling chamber for various trajectories of the opening of PRV and Ma *number change*. Good comparisons between the results predicted from the program and experimental data obtained subsonic Mach numbers in the existing 0.6m wind tunnel are shown. Predictions for VMFN operation show that the settli chamber pressure rapidly builds up towards the value of storage tank pressure, when the VMFN nozzle throat reduces fro Mach 1.0 to Mach 4.0 condition, presumably due to constriction of the flow passage at the first throat. Likewise, t pressure rapidly falls when the VMFN reverses from Mach 4.0 to 1.0 condition. By suitably controlling the initial openi and the trajectory of opening and closing of the PRV, it is possible to ensure that the stagnation pressure in the settli chamber is always greater than the minimum (running) pressure that is necessary for stable flow in the test sectio However, it is seen that during the transition from Mach 1.0 to 4.0 and vice versa, the free-stream dynamic pressu overshoots to relatively high values, which has significance on model and balance design for aerodynamic force a moment measurements at supersonic Mach numbers in the 0.6m wind tunnel.

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